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STUDIES FOR STUDENTS.

GENETIC RELATIONSHIPS AMONG IGNEOUS ROCKS.

It is desirable that the student of igneous rocks should appreciate the fundamental relationships existing between various kinds of igneous or eruptive rocks so far as they are understood at the present time, in order that he may form a proper idea not only of what an igneous rock actually is, but also of the uses and limitations of the terms by which they are designated. So it has been thought desirable to present, in an elementary form, some of the data and opinions bearing upon the genesis of different kinds of rock magmas.

It can be shown that all eruptive rock masses, whether emanating from volcanic vents at the surface of the earth or found enclosed within such vents, or confined to fissures not immediately connected with actual volcanoes, with the exception of certain infrequent occurrences of sandstones, which have been forced, while in a loose and incoherent state, into cracks—it can be shown that all ordinary eruptive masses were in a completely molten or fused condition before solidifying into the rocks they now are, and hence the terms eruptive and igneous are practically synonymous.

The igneous mass or molten magma, as we know by observations at active volcanoes, may obtain a liquidity comparable to that of water,¹ which, of course, would obtain for different temperatures in the case of magmas having different chemical compositions; the less silicious magmas reaching this liquidity at a somewhat lower temperature than the more silicious ones. During the process of cooling, magmas become gradually more

¹ JAMES D. DANA: *Characteristics of Volcanoes*, etc. New York, 1891, p. 143.

viscous, and crystallization generally takes place, but the two are in a measure independent operations, and the viscosity may be advanced so rapidly that crystallization is more or less completely prevented and glassy rocks result. According to the conditions under which rock magmas cool solidification will be accompanied by more or less complete crystallization. The size also of the crystals will vary with the rate of cooling, and the general texture of the rock will be affected. Different parts of one rock magma may experience different conditions of cooling, and there will result a variety of textures or structures within the mass. It may be that the textural differences are sufficiently pronounced to be given distinctive names, which become the terms by which certain kinds of rocks are designated; for example, granite, porphyry, pearlite, pumice, etc. There is then a relationship between certain kinds of igneous rocks which exists because of different conditions which have attended the solidification of various portions of one body of magma, or of several magmas alike in other respects. The significance of this relationship was long ago appreciated by James D. Dana,¹ who maintained that the textural differences among rocks were mainly due to the physical conditions under which they consolidated; an idea ably advocated and corroborated by Judd,² and more recently substantiated by numerous observations in many localities.

Igneous rocks often differ from one another in mineral and chemical composition; in fact, some kinds differ so widely from one another in a mineralogical sense that they possess no mineral in common. And most kinds contain the minerals which may be common to them in quite diverse proportions, and associated with various other species. Chemically they consist of the same essential constituents in variable proportions, the variations being within certain limits. But the proportions are so far from being

¹United States Exploring Expedition during the years 1838-1842, under the command of Charles Wilkes, U. S. N., 4to. Philadelphia, 1849, Vol. 10, Geology, p. 372 *et seq.*

²J. W. JUDD: On the Ancient Volcano of the District of Schemnitz, Hungary. Quart. Jour. Geol. Soc., 8vo, Vol. 32, 1876, p. 292 *et seq.*

fixed for similar kinds of rocks that it would be almost impossible to find two instances in which the proportions between the essential ingredients were exactly the same. The independence of many kinds of igneous rocks might seem at first thought to be clearly established by these mineralogical and chemical divergences. This apparent independence disappears when a great number of rocks are investigated. It is found that few rocks contain the same minerals in any given proportion, and that the variable proportions of minerals produce varieties of rocks which grade insensibly from one extreme of mineral composition into another. Intermediate varieties of rocks which form transitions from one type, or distinct kind, to another have been recognized for many years. But it is becoming more and more evident that the so-called type-rocks are not more abundant in nature than the intermediate forms. It is found that particular kinds of rocks may preponderate in one region and the intermediate varieties be subordinate, but that in other localities the relations may be reversed, and the so-called transitional forms may prevail.

The mineralogical gradation of one kind of rock into another is indicated not only by the comparison of all known varieties of igneous rocks, but more especially by the study of all the occurrences of such rocks in any region where they are abundant. The absence of distinctive types, and the presence of all possible varieties intermediate between the extremes is the most noticeable characteristic. Moreover, the transitional variations are not simply represented by slightly different bodies of rock, but they may often be found to exist within one continuous rock mass. Thus, a large body of rock may change in mineral composition from one spot to another by the most gradual transitions, giving rise to constitutional facies of the main mass. Again, it is found that a large body of rock, which may be nearly homogeneous throughout, exhibits certain mineralogical facies which are like the main portion of some other rock-body in the same region; so that the subordinate variety in one mass is the predominant form in another.

The ability of a rock magma to change in chemical composition in different parts, so as to crystallize into different mineral combinations which correspond to mineralogically diverse rocks, does not appear to be limited to small volumes of magma, but shows itself on quite different scales; sometimes confined to a narrow dike, at others acting throughout a large mass thousands of feet in diameter. That which is seen to have taken place within a comparatively limited volume of molten magma might be reasonably assumed to be possible within much greater volumes. Nevertheless it does not necessarily follow that it has done so; conditions which may have brought about the change in one case may not exist in another.

The probability that such changes have taken place in great reservoirs of molten magma, and have brought about the chemical and mineralogical differences among igneous rocks, finds its support in other evident relationships than those of facies and the gradual transitions in mineral composition between the kinds of rocks. The nature of this evidence is twofold and consists, first, in the existence of associations of various kinds of igneous rocks in volcanic regions; and second, in chemical and mineralogical diversity between different associations of rocks, that is, between groups of rocks belonging to different regions. The association of various kinds of rocks in particular volcanic districts, and their constant recurrence in company with one another in widely distant parts of the world impressed itself upon the minds of Scrope,¹ Darwin² and Dana³ in the first half of the present century, and led them to the opinion that the various kinds of lavas thus associated must have originated from some common source, that is, from a common molten magma, by some process of separation or differentiation.

Subsequently, as the chemical and mineralogical constitution of rocks became more readily determinable, it was discovered that there were chemical and mineralogical characteristics of

¹G. P. SCROPE: *Volcanos*, 8vo, London, 1825.

²CHARLES DARWIN: *Volcanic Islands*, 8vo, London, 1844.

³Loc. cit.

whole groups or associations of rocks which distinguished them from groups in other regions. This was noticed by Judd in studying the volcanic rocks of Hungary and Bohemia, and was afterwards clearly expressed by him in defining *petrographical provinces* as districts "within which the rocks erupted during any particular geological period present certain well-marked peculiarities in mineralogical composition and microscopical structure, serving at once to distinguish them from the rocks belonging to the same general group, which were simultaneously erupted in other petrographical provinces."¹ A striking illustration of the individuality of a petrographical province is found in the unusual group of rocks described by Brögger,² from the region of Christiania. They are characterized by a high percentage of sodium and a consequent abundance of alkali minerals. Brögger calls attention to the remarkable fact that the greater part of the rocks in this district are absolutely peculiar to the locality, or nearly so, and have not yet been found in any other part of the world. The association of special kinds of rocks in different localities has also been pointed out by Rosenbusch,³ and urged as evidence of a genetic relation between the rocks so grouped.

Certain chemical characteristics of special geographical groups of rocks become apparent when all of the chemical analyses are systematically compared and their variations plotted graphically, as has been done by the writer for the rocks of particular localities in the Yellowstone National Park, and for those of Vesuvius and vicinity, and of Pantellaria.⁴ It is observed in these cases that the relations of the alkalies to one

¹J. W. JUDD: On the Gabbros, Dolerites and Basalts of Tertiary Age in Scotland and Ireland. *Quart. Jour. Geol. Soc.*, Vol. 42, p. 54, 1886.

²W. C. BRÖGGER: Die Mineralien der Syenitpegmatitgänge der Südnorwegischen augit- und nephelinsyenite. *Zeitschr. für Kryst. u. Min.*, 8vo, Leipzig, 1890, Vol. XVI., p. 83.

³H. ROSENBUSCH: *Microskopische Physiographie der massigen Gesteine*, 8vo, Stuttgart, 1886, pp. ix., 600, 628, 767, 795, 809, 810, 821. Also in *Mineral. und petrogr. Mitth.* XI., 1890, p. 445.

⁴J. P. IDDIGS: The Origin of Igneous Rocks. *Phil. Soc. Washington, Bull.* Vol. XII., 8vo, pp. 89-214, Pl. 2. Washington, 1892.

another and to the other constituents is characteristic of the rocks of each group. A genetic relationship is clearly indicated, and it appears that the various rocks in each locality have been derived from a general magma peculiar to the locality.

The distinguishing characteristics of the rocks of different petrographical provinces which may be observed in their chemical composition also find expression in certain mineralogical peculiarities. Thus the presence of a relatively high proportion of potash will insure an abundance of potash-bearing minerals, as at Vesuvius. The relatively high percentage of soda in the rocks of Pantellaria, together with low alumina and relatively high ferric oxide, determines the prevalence of alkali-feldspars rich in soda, and of soda-bearing ferro-aluminous silicates, ænigmatite or cossyrite. The less prominent position of the alkalis in the rocks of Electric Peak and Sepulchre Mountain, and the relatively higher percentages of magnesia and iron oxide leads to the very general presence of orthorhombic pyroxene in these rocks, which is in contrast to the less magnesian and more alkaline rocks of Central France and Germany. The abundance of alkalis and general preponderance of soda in the rocks of the Christiania district expresses itself in the abundance of the alkali-feldspars and feldspathic minerals, and in the prevalence of acmite- and riebeckite-molecules in the pyroxenes and amphiboles.

From this it follows that certain rocks belong in particular natural series or groups, and are absent from others, and that two natural series of rocks, when arranged according to the percentages of silica, may grade through similar ranges of silica, but may each embrace different kinds of rocks. Thus :

Silica Percentages.	<i>Yellowstone Park.</i>	Silica Percentages.	<i>Vesuvius and Ischia.</i>
48-53	Basalt.	46-55	Leucitophyre.
55-62	{ Pyroxene-andesite.	55-62	Trachyte.
	{ Hornblende-andesite.		
64-68	{ Hornblende-mica-andesite.		
	{ Dacite.		
70-75	Rhyolite.	69-71	Rhyolite.

In such series it happens that rocks bearing the same name differ in certain mineralogical respects, and are really more

closely allied to the chemically nearest variety in their own group than they are to the rock of the same name in another group.

It must not be inferred from the facts just given that every natural group of rocks has some peculiarity which distinguishes it from every other group. There are many natural groups or petrographical provinces, the rocks of which are identical in the minutest detail with those of neighboring or distant regions. And the limits or boundaries of such provinces are not sharply drawn in nature. In some regions the transition from one province to another appears abrupt, in others very gradual. Thus, while certain provinces exhibit distinct mineral and chemical characteristics, others appear to possess characters of several provinces.

Recognizable chemical differences may exist between groups of rocks within less than a hundred miles of one another, and again broad general features may be persistent, or at least may be prevalent, over vast areas of the globe. Within these areas, of course, subordinate variations may exist. The most impressive illustration of this law is furnished by the igneous rocks of the two continents of North and South America. The great belt of Cordilleras and parallel ranges stretching along the western side of North America abound in igneous and volcanic rocks which belong to a quite uniform petrographical province, extending from British Columbia to Mexico and Central America. They are not specially rich in alkalies, and are characterized by a very general presence of the ferro-magnesia mineral, hypersthene; local variations occur. As the eastern portion of this mountain system is approached from the west a gradual increase in alkalies is noticeable, and rocks bearing nepheline, leucite and more frequent alkali-feldspars make their appearance, containing alkali-bearing ferro-magnesian minerals. These have already been described, from Montana, Wyoming, Dakota, Colorado and Texas, and are especially well developed in Arkansas. Similar eruptive rocks have been found in the eastern portion of the continent, in New Jersey, New England and Canada.

In South America the great Cordilleran system of the Andes presents a petrographical province identical, chemically and mineralogically, with those of the North American Cordilleras, and which appears to extend throughout its entire length. In the eastern part of the continent and on the islands off its coast the petrographical province is in turn identical in many respects with the eastern province of North America; the correspondence being most pronounced between the rocks from Brazil, described by Derby¹, and those from Arkansas described by J. Francis Williams.²

The chemical and mineralogical qualities or peculiarities which characterize the rocks of particular groups, and at the same time serve to distinguish them from those of some other groups, are like family traits of character, and suggest the intimate relationship and common origin of all of the igneous rocks of the group. They prove conclusively that the varieties of rocks occurring at a particular center of eruption, or in a volcanic district, have been derived from some magma common to the district by a process of differentiation similar to that which has caused smaller bodies of molten magma to become chemically heterogeneous and has produced mineralogical facies.

That the process which has produced the many kinds of igneous rocks in any region, with all their transitions into one another, was a process of differentiation of an originally homogeneous magma, and not the compounding of two or more different ones, is shown by the geological relationships between the various bodies of rock belonging to a volcanic center; more especially the order in which they have been erupted. A process dependent upon any set of physical conditions, which continues active for long periods of time must yield results that are to a very considerable extent functions of time, that is, they must be

¹ O. A. DERBY: On Nepheline Rocks in Brazil, with special reference to the Association of Phonolite and Foyaite. *Quart. Jour. Geol. Soc.* 8vo, London, Aug., 1887. Also *The Tinguá Mass.* *Ibid.*, May, 1891.

² J. FRANCIS WILLIAMS: The Igneous Rocks of Arkansas. *Annual Report of the Geological Survey of Arkansas for 1890.* Little Rock, 1891.

accumulative. Hence, if the process is one of synthesis or commingling, the mixture should be the more complete the longer the process has been in operation. On the other hand, if the process is one of differentiation the separation should be the more perfect as time goes on. The various bodies of rock occurring in a large volcanic region have been erupted at widely different times, and while belonging to a connected period of volcanic activity may often represent the lapse of ages. Their genetic relationship has been the result of some active principle coëxtensive with this vast time, and persistent or intermittent; the effect in either case must be accumulative.

It is found in all regions carefully investigated that there is a sequence in the eruption of different varieties of rocks which is most characteristic. From the nature of the causes leading to the extrusion of volcanic lavas, the irregularities of the conduits through which they reach the surface and the probable diversity in the physical conditions obtaining in different regions, it is to be expected that the course of events will not be the same in all cases, or constant in any one instance. Hence the sequence of rocks will not be uniform for all regions, nor will it necessarily be simple in any case. The sequence discovered by von Richthofen,¹ when expressed in general terms, is of very wide application, and is to the effect that the earliest eruptions are of rocks having an average or intermediate composition, and that subsequent eruptions bring to the surface magmas of more and more diverse composition; the last eruptions producing the most diverse forms. The transition from a magma of intermediate composition to those of extremely divergent composition, is clearly the result of a process of differentiation. "This correspondence between the petrographical and the geological succession," as Brögger² remarks, "appears to prove conclusively a genetic connection between successive eruptions." The same conviction has been expressed by Geikie, Teall and others. Evidences of the mixing

¹F. von RICHTHOFEN: *The Natural System of Volcanic Rocks*, 4to. San Francisco, 1868.

²Loc. cit. p. 83.

of different rock magmas to form an intermediate modification are exceedingly local, and appear to be confined to narrow limits along the junction of one body of rock with another.

The genetic relationship between the various kinds of igneous rocks belonging to a center of volcanic activity, which is plainly indicated by their chemical, mineralogical and geological relationships, is in the nature of a generic connection. They have originated from some common magma or parent stock, and to a very large extent are characterized by whatever distinguishing peculiarity was characteristic of the parent magma. They are in this sense consanguineous. The presumably homogeneous parent magma has become heterogeneous by some chemico-physical process or processes, so that different portions of it have different chemical constitutions. The differentiation undoubtedly takes place according to fixed laws and within limitations affected by the original constitution of the magma, and by the external controlling conditions or agencies. Further than this we shall not venture in the present article. It will be sufficient to consider some of the consequences of the general principles of magmatic differentiation.

First. If differentiation is controlled by external agencies or conditions, such as changes of temperature and pressure, which depend largely on the environment of the magma, then the results of differentiation should vary when the external conditions vary. It is not to be expected, therefore, that similar magmas will always yield the same results when differentiated, within certain limits. They may have experienced quite different physical conditions. The more uniform the conditions the more concordant the results.

Second. Since the process of differentiation requires time, is progressive, and, from geological evidence already alluded to, often continues for ages, it follows that eruptions from a reservoir, where the process of differentiation is taking place, will draw off magma whose constitution will depend on the phase of differentiation attained by the parent magma. The phase will naturally depend on the time at which the eruption takes place.

Moreover, since the process of differentiation necessitates the coëxistence of differently constituted derived magmas in various parts of the parent body or reservoir, the kind of magma drawn off at an eruption will also depend upon the portion of the reservoir drawn from.

Third. If, in a given region of eruptive rocks, each body of rock was the immediate solidification of the magma drawn directly from one common reservoir, they would represent the phases of differentiation in the parent magma at the time when the eruptions took place. If, however, the magma drawn from the reservoir did not solidify immediately, but remained in a molten condition within the fissure or conduit, a still further differentiation within this derived magma might take place under conditions imposed by its new environment. In this manner differentiation might proceed at quite different rates and possibly with diverse results in the parent magma and in the derived magma. Material, then, which, through subsequent eruption, might come to a place where it could solidify, might be derived from the parent magma or from the derived magma, and would represent different phases of differentiation. Either set of conditions of eruption may exist in nature, and much more complex ones. The first may very well be found in great fissure eruptions such as have taken place in western America. The second are probably represented by groups of volcanic vents. Both are simply modifications of eruptive processes, and differ in no essential respect.

The genetic relationship of rocks belonging to one center of eruption, or to one group of centers, or to one petographical province, makes plain the fortuitous character of so-called rock types; the constitution of any rock mass depending primarily upon the phase of differentiation, and on the portion of the reservoir let out. It proves the fundamental character of the variability in composition of such rocks, both as between different bodies of rock and also within the mass of one continuous body in many cases. The degree of homogeneity in a rock body will depend upon the relation of its volume to that of the reservoir

from which it was drawn, and the conditions of differentiation existing there, and, further, upon whether it has undergone subsequent differentiation within itself.

The textural variations which were discussed in the first part of this paper, and which may exist in diverse portions of one rock body, or in different bodies of similar magmas, add still further to the complexities in solidified magmas. Rock magmas are thus known to vary frequently in chemical composition, mineral composition and texture. Names of rocks which are defined in terms of these three characters, can only apply to that portion of a rock body exhibiting the characters specified. Other parts of the mass will have different names, and to this extent be different rocks. The student should therefore recognize the difference in the idea conveyed by the term *rocks* as ordinarily used, and that which is involved in the expression *rock-body*, as a geological unit.

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